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Modelling, Design & Analysis of Bidirectional Interleaved DC to DC Converter

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***Abstract:** In today's scenario, global warming is a major issue for the environment. To fight this issue, the shift from non-renewable sources to renewable sources and the use of electric vehicles are increasing day by day. The bidirectional converters are the crucial device to run such renewable plants and electrical cars, where bidirectional power exchange is needed. To make a more efficient and reliable system, advanced or interleaved/multiphasing technologies are required.*

A new interleaving bidirectional DC-to-DC converter is proposed in this paper to minimize the input current ripples and increase power handling capacity. This paper mainly describes the analysis of interleaved bidirectional converters in steady-state and two- and three-phase interleaved converter closed-loop simulations in both modes. The results show the interleaving of inductor-currents and stiff output voltage along with the bidirectional power flow capability, and the waveforms of interleaved inductor current, input current ripples, and output voltage are presented.

***Keywords:** Global Warming, Renewable Energy, Electric Vehicle, Bidirectional Converters, Interleaved Topology, Power Handling Capacity, Current Ripples*

I. INTRODUCTION

The global push for sustainable energy solutions, driven by depleting fossil fuel reserves and environmental concerns, has spurred advancements in power electronics [1]. Key among these innovations are bidirectional DC-DC converters, originally designed for motor drives to control speed and braking [2]. Today, their application spans crucial sectors like DC drives, microgrids, renewable energy storage, and hybrid electric vehicles, being essential in managing power flow and stabilizing voltage under high-power situations [3]. However, these converters are facing some challenges in high-power applications, such as due to large current flowing in the system, the size of the inductor increases, so the converter size increases. Also, due to the switching phenomenon, fluctuations are generated in the input current, so to overcome these issues, the interleaving topology in the converter is introduced. This topology involves multiple phases that are connected in parallel with each other to share the power load [1].

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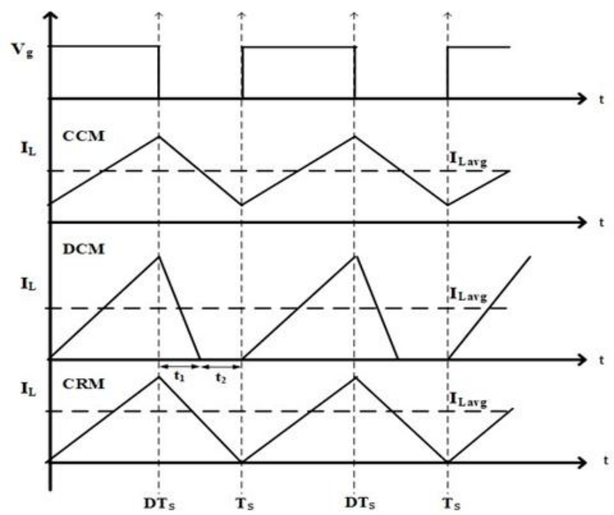
This topology lowers the current ripples, decreases the overall size of the converter by reducing inductor bulk [2], reduces the stress on switches, and enhances the performance of the converter by making it more efficient & reliable [3].

In an inductor-based converter, during the switching cycle, the explanation of how current is flowing from the inductor of the converter is known as the current-conduction mode of the converter. Figure-1 illustrates the current conduction mode waveform for this type of converter. Each current conduction mode has different specialties for different needs, stability, & balancing efficiency across different loads as per the requirements. Here, CCM is a continuous-conduction mode, where the inductor-current is flowing continuously as the inductor conducts continuously. This mode is preferred for high-power applications because the current doesn't fall to zero during the switching cycle. DCM is a discontinuous-conduction mode of converter where the inductor current continuously increases until the turn-on condition and starts decreasing at t1 during the turn-off period, and remains at zero until t2 or at the end of the interval. It is preferred for low-power applications because in high-power it increases the ripples in current. CRM is a critical conduction mode; in this mode, the inductor current starts decreasing until it becomes zero, and then again it starts rising. This mode reduces switching losses and is preferred for low-power applications.



[Fig.1: Interleaved Inductor Current Conduction Mode CCM, DCM and CRM] [1]

This paper explores the fundamental principles & performances of bidirectional DC to DC converters with simulation in closed-loop of two-phase and three-phase interleaving configurations in boost mode by MATLAB/SIMULINK.

By studying simulation approaches and their impact on converter design, the aim is to enhance efficiency and reliability in modern power management applications.

II. BIDIRECTIONAL DC-DC INTERLEAVED CONVERTER WITH N PHASE

The N power modules in a Bidirectional DC-DC interleaved converter with N phases are linked in parallel, and gate-signals of them are phase shifted by, $\frac{360°}{N}$ so that their phases operate out of phase with one another. This arrangement divides the input current across parallel paths. Due to the phase shift, the current ripples from each phase can cancel each other, leading to a significant reduction in overall ripple [1]. The phase interleaving technique ensures smoother current delivery to the load, reducing ripple and enhancing efficiency, improving the converter's performance and stability [2].

This converter is operating mainly in two modes:

1. **Boost-Mode:** In order to satisfy the Dc-bus voltage specifications, the converter raises the input voltage. The DC bus receives electricity from the battery when it discharges, and the power-modules each receive an equal amount of current [4]. The total current flowing through all of the inductors in a battery is its total current. For an N-phase system, the battery current is the combined total of the currents through all the inductors. This operational mode is essential in electric vehicle (EV) applications [8] and is known as the driving mode.
2. **Buck-Mode:** Allowing the battery to charge, which is the reverse of the boost mode and transferring power from the Dc-bus to the battery occurs in this mode [4]. Additionally, there is an equal distribution of negative Dc-bus current (ib) among all phases. In an N-phase converter, this mode is commonly referred to as regerative mode [8] in electric vehicle (EV) applications.

For the N-phase converter, the mathematical way to determine phase shift, overall inductor current and total no. of phase are given below,

(a) The phase shift that is imposed between the converter's successive legs is determined by: [3]

$$\theta = \frac{360°}{N} \dots \quad (1)$$

(b) The combined current of the inductor is shown as: [3]

$$I_b = \frac{P}{V_s} \quad \dots \quad (2)$$

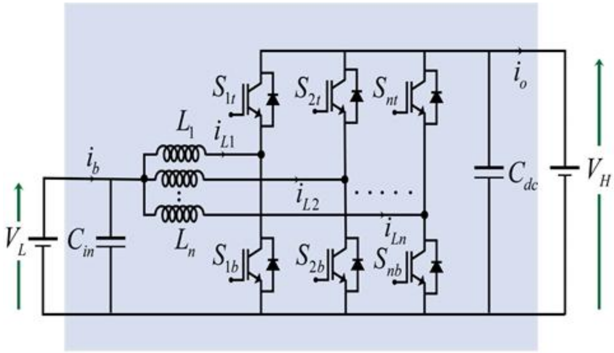
Where P signifies the converter's power level, and the battery voltage is Vs.

(c) Total no. of phases is calculated by: [3]

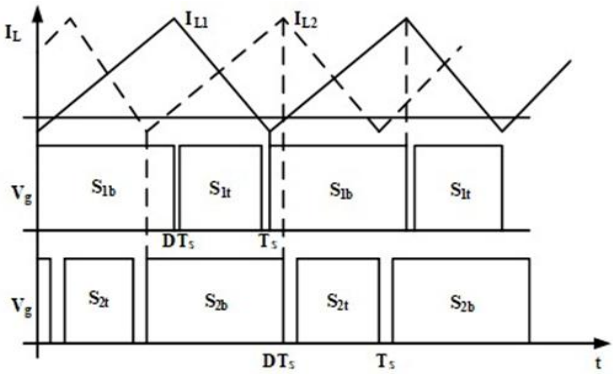
$$N = \frac{I_b}{I_{L\max}} \quad \dots \quad (3)$$

Where, ILmax is the inductor currents per phase maximum value available commercially according to specifications.

The schematic depicted in Figure-2 is of a Bidirectional interleaved DC to DC converter with N parallel-connected modules. Figure-3, highlights the corresponding inductor current waveform and the gate signals for the switches.



[Fig.2: N-Phase Interleaved Converter] [3]



[Fig.3: Gate Signals and Inductor Current Waveform for N-Phase Interleaved Converter] [3]

III. DESIGN OF FILTER PARAMETERS

The Bidirectional DC to DC interleaved converter operates in both boost and buck modes to manage voltage levels efficiently. In boost mode, it raises the battery voltage (Vs) from 24V to a DC bus voltage (Vdc) of 48V, while in buck mode, it lowers the DC bus voltage back to 24V to recharge the battery [4]. The load power level (Pdc) is considered as 1kW and switching frequency (f_{sw}) is considered as 20 kHz.

During boost mode the converter operates with a duty ratio of: [6]

$$D = \frac{V_{dc}-V_s}{V_{dc}} = \frac{48-24}{48} = 0.5 \quad \dots \quad (4)$$

Inductor value is obtained from, [2]

$$I_{Ltotal} = \frac{P_{dc}}{V_L}, where V_L = V_s = 24$$

$$= \frac{1000}{24} = 41.66A$$

$$i_{L1} = i_{L2} = i_L = \frac{i_{Ltotal}}{2} = 20.83A$$

$$\triangle i_L = 20\% of\, i_L = 4.166A$$

$$L = \frac{V_s.D}{\Delta i_L.f_{sw}} = \frac{24\times0.5}{4.166\times20\times10^3} = 0.15mH \quad \dots \quad (5)$$

DC link capacitor is obtained from, [7]

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$$C_{dc} = \frac{D.V_{dc}}{R_{dc}.\Delta V_{dc}.f_{sw}}$$

$$where, R_{dc} = \frac{V_{dc}^2}{P_{dc}} = \frac{48^2}{1000} = 2.304\Omega$$

$$\Delta V_{dc} = 2\% of V_{dc} \quad \dots \quad (6)$$

$$= 0.02 \times 48 = 0.96$$

$$C_{dc} = \frac{0.5\times48}{2.304\times0.96\times20\times10^3}$$

$$= 0.54\mu F$$

During buck mode the converter operates with duty ratio of: [5]

$$D = \frac{V_s}{V_{dc}} = \frac{24}{48} = 0.5 \quad \dots \quad (7)$$

To ensure the converter functions correctly, essential parameters like the duty ratio, inductor value, and DC link capacitor value are meticulously calculated. These parameters are crucial for maintaining stable and efficient performance in both operational modes, allowing the converter to adapt to different power requirements seamlessly.

IV. SIMULATION AND RESULS

The closed loop simulations are performed to analyse both two and three-phase versions of the converter in charging and discharging modes using MATLAB/SIMULINK.

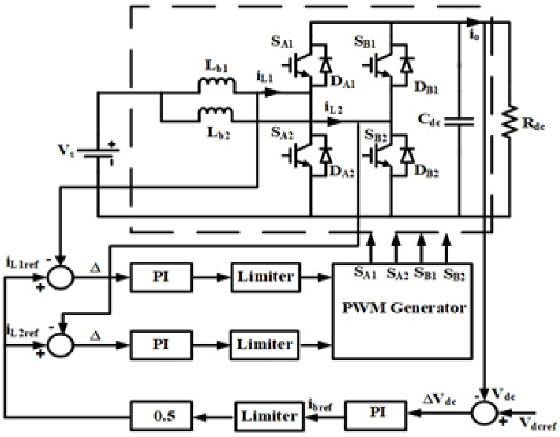
When in the boost (discharging) mode, the voltage on the high-voltage Dc-bus is raised to 48V by a 24V, 42Ah battery on the low-voltage side. In order to activate the buck (charging) mode, disconnect the HV side load and attach a 48V, 42Ah battery to the DC bus.

This configuration ensures the interleaved converter can efficiently handle both voltage increase and decrease. The simulation demonstrates the converter's capability for bidirectional power flow, underscoring its flexibility and robust performance in varied operating conditions. The Bidirectional DC to DC interleaved converter is intended to support a 1 kW load power level and operates at a 20 kHz switching frequency, as outlined in Table 1.

Table 1: Simulation Parameters for Interleaved Converters

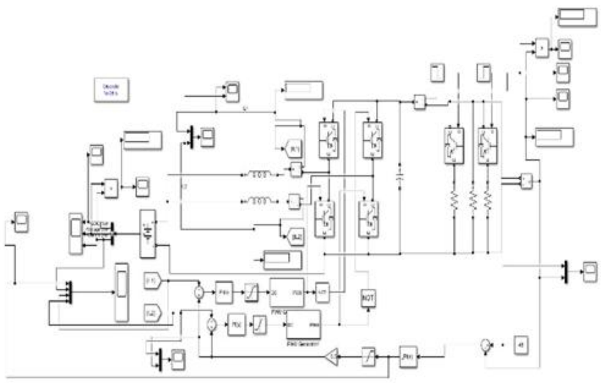
Parameters	Specifications
Rated Power	1 kW
Switching Frequency	20Hz
Input Inductance	0.5 mH
Output Capacitance	1.2 µf
Battery Voltage	24 V/ 48 V, 42 Ah
Output Voltage	48 V
Load Resistance	4.4 Ω
Inner Current Loop Controller Gains (Kp, Ki)	0.058, 1
Outer Voltage Loop Controller Gains (Kp, Ki)	2, 40

A. Simulation and Results of Interleaved Converter for Two-Phase



[Fig.4: Schematic Diagram of Control of Two-Phase Interleaved Converter] [9]

The simulation model of dc to dc interleaved converter for two-phase in closed-loop [9] is shown in figure 5,



[Fig.5: Simulation Model of Two-Phase Interleaved Converter in Closed-Loop]

Figure-5, shows a two-phase Bidirectional interleaved converter with a phase shift of 180-degree. To ensure a consistent output voltage (V_{dc}) and accurate interleaving of inductor currents (I_{L1} and I_{L2}), a bidirectional DC-DC converter employs a control approach consisting of a voltage control loop outside and two inside current control loops.

The controller first determines the error voltage (Δv), which is the difference between the actual and desired output voltages. A safe battery reference current i^{ref}_b is obtained by processing the error voltage (Δv) using a PI controller.

For safety reasons, the battery reference current undergoes a rate-limiting process to prevent excessive discharge. This generated current is divided and compared to the actual inductor currents (I_{L1} & I_{L2}). The controller then divides this reference current equally and compares it separately with the currents flowing through each inductor (I_{L1} & I_{L2}). These comparisons produce error currents (Δi) for each inductor, which are individually processed by separate PI controllers to determine the duty cycles (d1, d2). Subsequently, the duty cycles d1 & d2 are fed into a PWM generator, which generates gate signals for the switches.

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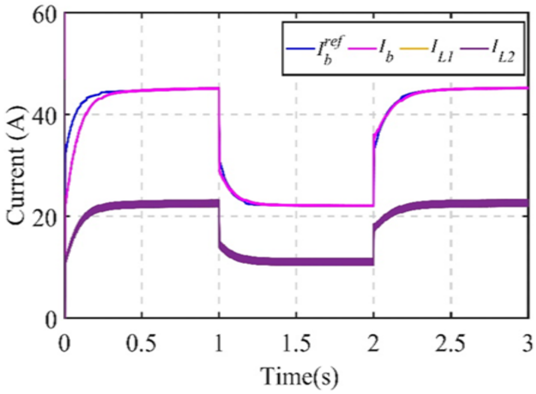
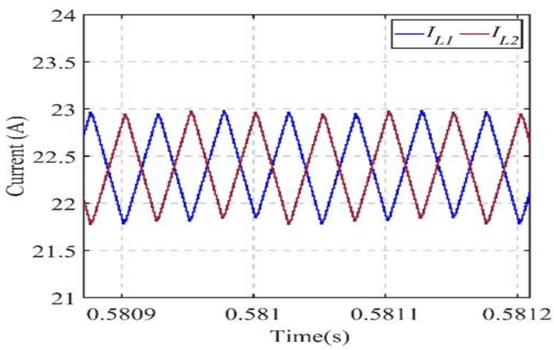
i. Simulation Results of Interleaved Converter for Two-Phase

For a two-phase interleaved converter with load variation in boost mode, the simulation results are depicted here. In the simulation, the system initially operates with a 1 kW load. At t = 1 second, the load is decreased to 50% of its initial value, and then at t = 2 second, the load returns back to its 1 kW rated rating.

Figures-6 and 7 illustrate the waveforms of battery current, battery reference current, each phase current of an inductor, and input inductor current ripples.



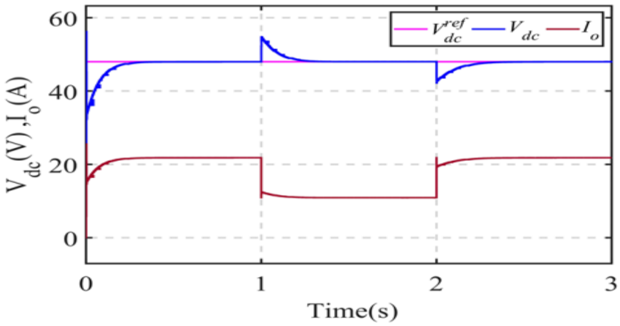
[[Fig.6: I_b^{ref}, I_b & I_{L1}, I_{L2}]]



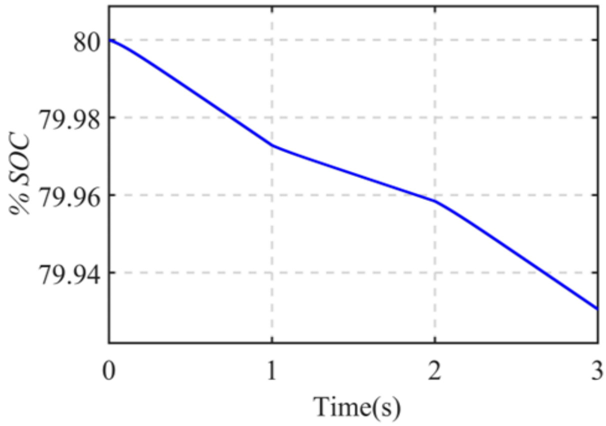
[Fig.7: Ripple Currents I_{L1} and I_{L2}]

From Figures-6 and 7, it is evident that the current of the battery (ib) closely follows the battery reference current. Moreover, the ripple in the inductor current is evenly distributed between the two phases, with each phase being shifted by 180 degrees.

The voltage controller is intended to preserve a consistent DC-bus voltage of 48V, which is clearly demonstrated in Figure-8. In this figure, you can also observe how the current fluctuates in response to changes in the load, indicating that the controller is effectively managing these variations to keep the voltage constant. The dc bus voltage, reference voltage and load current waveforms,



[Fig.8: V_{dc}, V_{dc}^{ref}, and I_o]

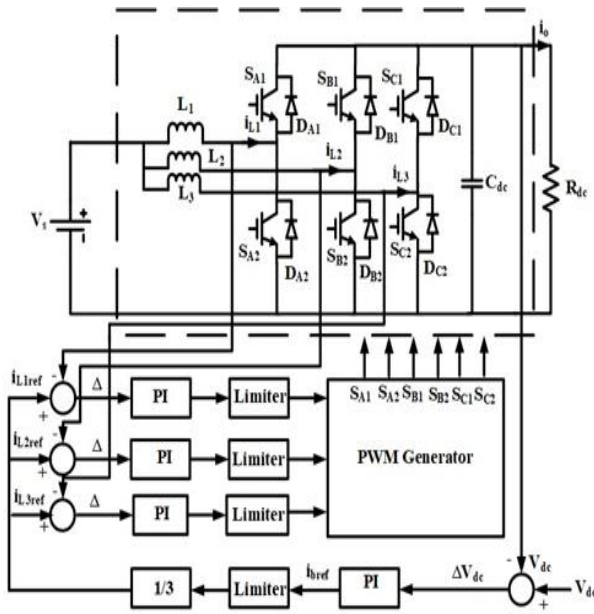


[Fig.9: % SOC of Battery]

Figure-9, illustrates the battery's %SOC (state of charge), showing a Down ward trend. This decline in %SOC indicates that the battery is discharging, which is expected during the boost-mode operation where energy is being supplied to the load. For the next part of the simulation, which involves the buck (charging) mode, the procedure changes.

The load connected to the high voltage (HV) side is removed, ensuring that there is no load to influence the voltage on that side. Subsequently, a battery with a voltage rating of 48V and a capacity of 42Ah is linked to the DC bus. This configuration permits the system to transition into charging mode, where the battery at the DC bus receives energy, effectively simulating the buck mode operation. This change in configuration helps in analyzing the system's performance under different operational modes—boost (discharging) and buck (charging).

B. Simulation and Results of Interleaved Converter for Three Phase



[Fig.10: Schematic Diagram of Control of Interleaved Converter for Three-Phase] [10]

The closed loop simulation model of interleaved converter for three-phase [10] performed in MATLAB/SIMULINK is shown here,

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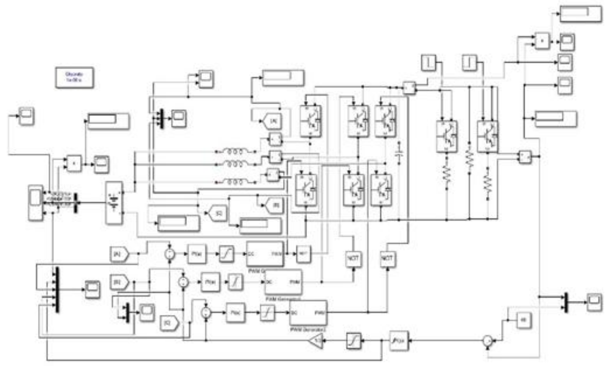


[Fig.11: Closed Loop Simulation Model of Interleaved Converter for Three-Phase]

This Figure shows an interleaved bidirectional converter for three phases with 120-degree phase shift [11]. To ensure a consistent output voltage (V_{dc}) and accurate interleaving of inductor currents (I_{L1}, I_{L2} & I_{L3}) in this converter, a control scheme comprising an outer voltage control loop and three inner current-control loops is employed in a bidirectional DC to DC converter [12]. The variations between the intended and real output voltage are represented by the voltage error (Δv), which is first calculated by the controller. After passing via a PI controller, the voltage error (Δv) is processed to provide i^{ref}_b, a safe battery reference current [13].

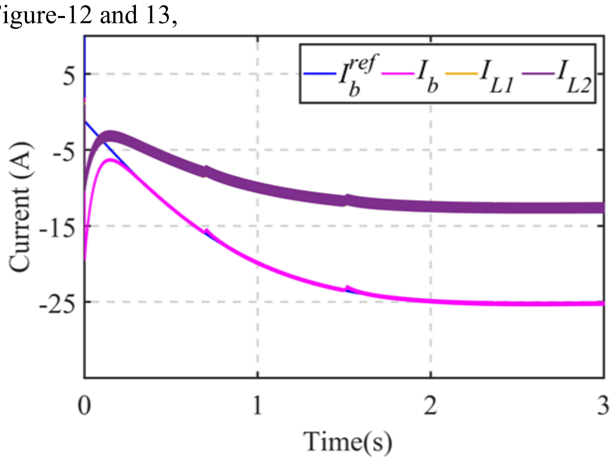
For safety reasons, the battery reference current undergoes a rate limiting process to prevent excessive discharge. The controller then divides this reference current equally and compares it separately with the currents flowing through each inductor [14].

These comparisons produce error currents (Δi) for each inductor, which are individually processed by separate PI controllers to determine the duty cycles (d1, d2 & d3) [15]. Subsequently, the duty cycles, are fed into a PWM generator, which generates gate signals for the switches.

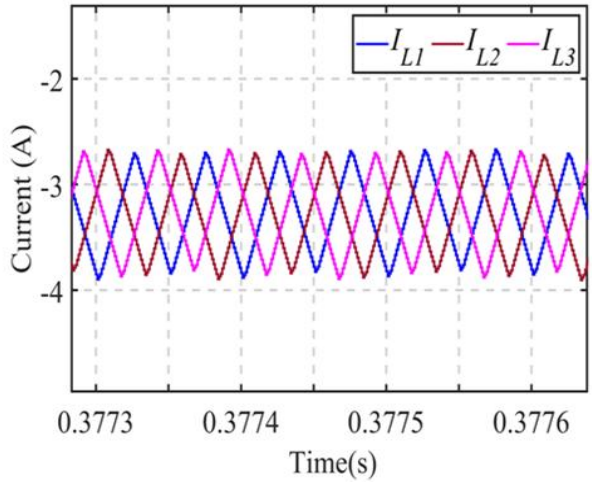
i. Simulation Results of Interleaved Converter for Three Phase

For a three-phase interleaved converter with load variation in boost mode, the simulation results are depicted here.

In the simulation, the system initially operates with a 1 kW load., The load at t = 1 second is decreased to 50% of its initial value, and then at t = 2 second, the load returns back to its 1 kW rated value. The current of the battery (ib), battery reference current, inductor current of each phase, and inductor input current ripples waveforms are shown in Figure-12 and 13,

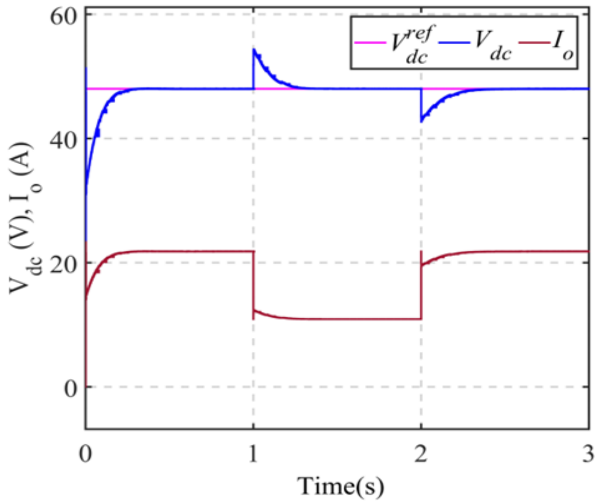


[Fig.12: I_b^{ref}, I_b and I_{L1}, I_{L2} and I_{L3}]

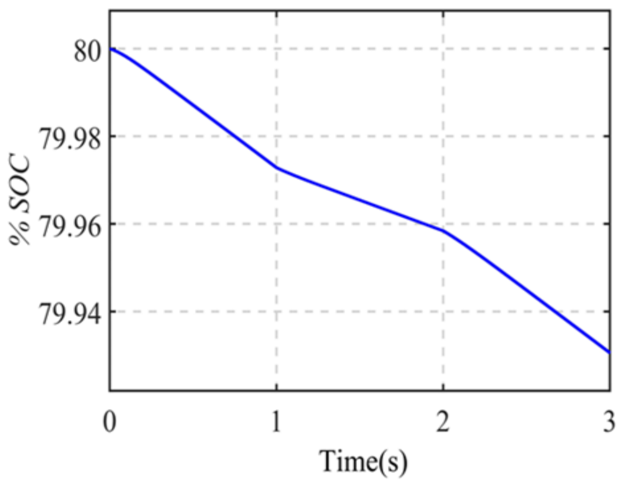


[Fig.13: Ripple Current I_{L1}, I_{L2}, I_{L3}]

From the Figures-12 and 13, it is evident that the current of the battery (ib) closely follows the battery reference current. Moreover, the ripple in the inductor current is evenly distributed between the two phases, with each phase being shifted by 180 degrees. The dc bus voltage, reference voltage, and load current waveforms, are shown in Figure 14.



[Fig.14: V_{dc}^{ref}, V_{dc} & I_o]



[Fig.15: % SOC Of Battery]

Figure-15, illustrates the battery SOC, showing a Downward trend. This decline in %SOC indicates that the battery is discharging, which is expected during the boost-mode operation where energy is being supplied to the load. For the next part of the simulation, which involves the buck (charging) mode, the procedure changes. The load connected to the high voltage (HV) side is removed, ensuring that there is no load to influence the voltage on that side. Subsequently, a battery with a voltage rating of 48V and a capacity of 42Ah is introduced to the DC bus. This setup permits the system to transition into charging mode, where the battery at the DC bus receives energy, effectively simulating the buck mode operation.

V. CONCLUSION

In this Research, the Bidirectional interleaved DC to DC converter's control & simulation are presented. Both the charging and discharging modes are used in the controller design and BDC simulation. The converter has the ability to control both the interleaving of inductor current and a steady output voltage. The converter can have bidirectional power flow based on both boost and buck mode of operation. The simulation's steady-state and transient findings under load fluctuation are deemed good. A comparative study of three-phase and two-phase interleaved converters is also conducted. A three-phase converter's input current and output voltage ripple are lower than those of a two-phase converter because the thermal distribution is correctly maintained. Additionally, a three-phase interleaved converter has reduced current stress across its switches.

VI. ACKNOWLEGMENT

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DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

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- **Funding Support:** This article has not been sponsored or funded by any organization or agency. The independence of this research is a crucial factor in affirming its impartiality, as it has been conducted without any external sway.
- **Ethical Approval and Consent to Participate:** The data provided in this article is exempt from the requirement for ethical approval or participant consent.
- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Authors Contributions:** The authorship of this article is contributed equally to all participating individuals.

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drives advancements in the electrical engineering domain.

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